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Fluid Mass and Thermal Loading Effects on the Modal Characteristics of Space Shuttle Main Engine Liquid Oxygen Inlet Splitter Vanes

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Presented herein is an analysis and evaluation of experimental modal survey test data on the variations of modal characteristics induced by pressure and thermal loading effects. Extensive modal survey tests were carried out on a Space Shuttle Main Engine (SSME) test article using liquid nitrogen (LN_2) under cryogenic temperatures and high pressures. The results suggest that an increase of pressure under constant cryogenic temperature or a decrease of temperature under constant high pressure induces an upwards shift of frequencies of various modes of the structures.

INTRODUCTION

In many situations, structures that are surrounded by fluids display high amplitude resonant oscillations, especially when the fluid is in a dynamic flow condition. A known mechanism for this resonance is the periodic vortex shedding as the flow encounters the structure and separates into turbulent flow patterns. The vortices normally result in steady and unsteady drag forces parallel with the flow and unsteady lift forces perpendicular to the flow direction. When the internal damping of the structure is very low, resonant oscillations can be created that induce structure/wake unstable vibrations that take place in unison reinforcing each other at a frequency near one of the natural frequencies of the structure.

To evaluate such environmental effects, a test was designed using a Test Article that consisted of the Space Shuttle Main Engine (SSME) Liquid Oxygen (LOX) inlet line, inlet splitter vanes, and manifold welded to a forged base ring (Fig. 1 and 2). The inlet splitter vanes were instrumented with semi-conductor strain gages and the leads were brought out through Conax fittings installed in an inlet adapter flange to a dummy Main Oxidizer Valve (MOV) connected to the LOX inlet line. External accelerometers were used on the inlet elbow to evaluate modal data on this component. Additionally, thermocouples were welded to the internal and external surface of the "tee" to allow monitoring of skin temperatures. This configuration allowed termination of the test item at boundaries considered to be realistic such that any measured response would be that expected to be seen in a complete engine. This hypothesis was evaluated by hanging test weights on the MOV inlet flange and evaluating response. These data comparisons are discussed later, but did show that the response changed.

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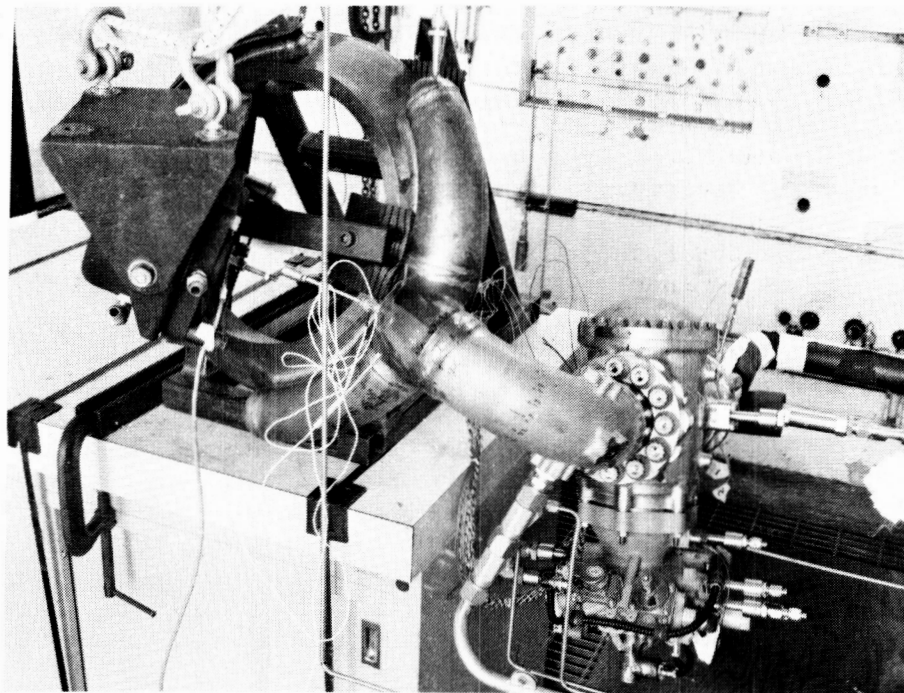


Fig. 1. Liquid Nitrogen Test Article

The results of these experiments that specifically addressed the issue of the effect of fluid pressure/mass and temperature variations on the frequencies of the SSME liquid oxygen inlet splitter vanes will be presented herein. The experiments consist of liquid nitrogen pressurization of the article from ambient to 4300 psi and under temperatures ranging from -40 to -240°F . Strain

gages located at various points on the splitter vanes recorded the strain levels under various pressure and temperature conditions (Fig. 2 and 3). Isoplots indicating vibration amplitudes versus frequency changes as a function of time will be presented and discussed. The influence of pressure variations under constant temperature and temperature variations under constant pressure on the natural frequency of modes between 3 to 5 kHz will be analyzed. Furthermore, a simple clamp was tightly attached to the LOX inlet elbow, near the splitter vane external edges, and its damping effect on the vane vibrations was analyzed through the strain gage data.

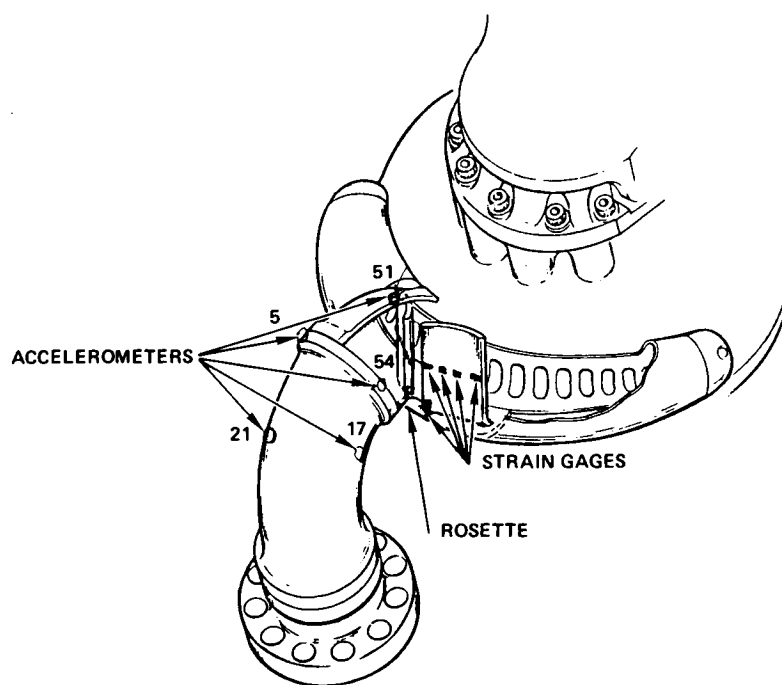


Fig. 2. SSME Main Injector LOX Inlet

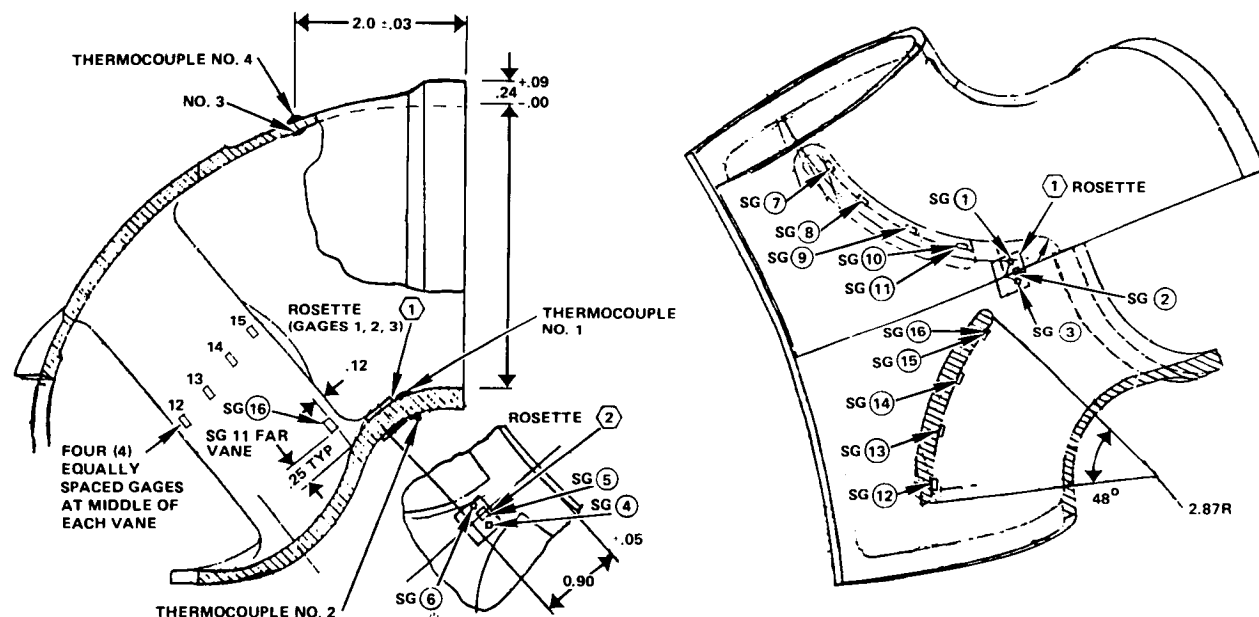


Fig. 3. Liquid Nitrogen Test Article Instrumentation Locations

The overall effect of increased pressure and/or decreased temperature was a shift of natural frequencies upwards--in some cases, significantly. Moreover, the presence of the clamp had the effect of damping out most of the vibrations of the splitter vanes and reducing their amplitudes appreciably. All indications lead to the conclusion that there is a strong nonlinear behavior of the structure interacting with the fluid.

PROBLEM DEFINITION

Vibration of structures in vacuum or air has been extensively studied. However, vibration of structures under the influence of a fluid medium has just recently raised the interest of researchers [1]. Whereas vibration of a metallic structure in air is virtually identical to that in vacuum, this is not the case with a structure that is in contact with a fluid. In the SSME, liquid oxygen enters the inlet tee (Fig. 2) at high velocity, high pressure, and cryogenic temperature, striking the splitter vanes and experiencing a division of main flow into the two sides of the tee into the injector. Thus, the splitter vanes are in the course of highly turbulent flow regimes. It is well known that in such severe environments, fluid/structure interaction can be potentially unstable and induce fluid-elastic instabilities [2].

The underlying objective of the present study program is to analyze the static effects of fluid pressure and thermal loadings on the splitter vane modal characteristics. Extensive experimental modal survey tests have been carried out at Rockwell International/Rocketdyne Division's Engineering Development Lab (EDL) regarding the static fluid mass, pressure, and thermal loading effects of various fluids under different temperature and pressure conditions on the modal characteristics of vibrating structures. The present article discusses the liquid nitrogen test results.

Theoretical Preliminaries

The liquid effect on natural frequencies of a structural vibration mode can be evaluated as the sum of fluid dynamic pressure distribution and the forces exerted by the structural surfaces. The elastic and acoustic problems are coupled by a feedback loop due to the influence of the radiation loading exerted by the fluid. This modifies the force that excites the structural vibrations, while the structural response changes, in turn, the radiation loading. This radiation loading sometimes takes the form of inertial forces and is comparable in magnitude to the inertia and elastic vibration forces in the structure [3].

The equation of motion for fluid/structure interaction problems can be derived from the Lagrangian [4]

$$L = (T_s + T_L) - (U + W) \quad (1)$$

where T_s is the kinetic energy of the structure, T_L is the kinetic energy of the fluid, U is the strain energy of the structure, and W is the potential energy of the applied loads. The potential function of an incompressible, nonviscous fluid must satisfy Laplace's equation

$$\nabla^2 \phi = 0 \quad (2)$$

where ∇^2 is the Laplacian operator, t is time, and ϕ is the potential function. The velocity vector of the fluid is given by

$$(\nu_x, \nu_\theta, \nu_r) = \left(-\frac{\partial \phi}{\partial x}, -\frac{1}{r} \frac{\partial \phi}{\partial \theta}, -\frac{\partial \phi}{\partial r} \right) \quad (3)$$

Under appropriate conditions, the velocity potential function can be approximated by

$$\phi = \phi(r) \sin(m\pi x/L) \cos n\theta e^{i\omega t} \quad (4)$$

where ω is the frequency, m is the number of axial half-waves, and n is the number of circumferential waves [3]. Under these assumptions and additional simplifications, it is possible to derive analytical approximation to the vane frequencies in the LOX inlet tee shell as a function of fluid pressure, temperature, and other structural parameters. Herein, we will not be concerned about the analytical developments. The interested reader can consult the references cited for details. The intent here is to present the experimental results and comment on their significance. The theoretical developments and predictions will be treated in a separate paper.

PROCEDURES AND APPROACH

The usual procedure of setting up and testing a structure was followed during the SSME Test Article modal survey experiments. The Test Article was appropriately isolated and measurements of strains and accelerations were taken. The strain and acceleration signals were processed through existing curve-fitting codes, and the results were then presented in various plots in the form of frequency response functions, power spectra, etc.

Instrumentation

Instruments utilized during the liquid nitrogen pressurization and low temperature tests consisted of:

1. A Genrad Micromodal Analyzer No. 2510 with appropriate signal conditioning devices, FM tape recorder, hybrid disk memory, and signal processor
2. A Goodman 5-lb high-frequency (300 to 5000 Hz) shaker with an appropriate connective quill (stinger) for steady-state, flat-random inputs, signal-input amplifiers, and filters (LP, BP, HP)
3. Twelve strain gages placed on four equidistant locations on the midspan of each vane, two at the bottom leading edge of each vane, in addition, two three-directional rosettes were placed externally on the top and bottom of the duct tee on the shell at the vane/shell interface (the strain gages were from Micromeritics with model Numbers WK-062 RB)
4. Six $2E-3$ piezoelectric accelerometers (Unholtz-Dickie) with charge amplifiers and signal conditioners) were placed on the elbow and the duct shell externally at locations 5, 17, 21, 51, and 54, respectively (Fig. 2, and 3)
5. Thermocouples
6. Pressure gages
7. Load cell
8. Miscellaneous filters, amplifiers, and other related equipment

Software

Several software routines were utilized during the modal survey tests. MODAL-PLUS by Structural Dynamics Research Corporation (SDRC) is a modal

analysis package that furnishes modal displacements, frequencies, and damping ratios, as well as other relevant data. Rocketdyne's EDL has Versions 7 and 9.2. The latter version is on the VAX computer system and has the advantage of speed and performance over Version 7.

Data acquisition software available at EDL consists of (1) Interactive Signal Analysis Package (ISAP) produced by Genrad, Inc., and DATUM put out by SDRC. The first program is useful in spectral analysis, cross- and auto-correlation, averaging time histories, as well as in generating transfer functions. Its resolution level involves 4096 lines/frame, which translates into 1600 frequency lines.

Data Reduction

The principal task that an analyzer performs is essentially estimating the Fourier transform or the spectral densities of signals in the time domain that are supplied as inputs. The process involves expressing a periodic time function as an infinite sum of sinusoidal functions with discrete frequencies. In each case, the inputs are digitized (by an A-D converter) and recorded as a collection of discrete values evenly spaced in the measurement period T.

There are a number of concerns that the engineer has to properly deal with in every modal survey test data reduction process. These are, in general, related to discretization approximation, and the fact that time histories are not infinite. Some of the abovementioned problems are referred to as aliasing (whereby high frequency signals are misinterpreted as low frequency signals due to insufficient sampling rate), leakage (whereby a single frequency signal might be interpreted as a multiple frequency, one due to finite length of time history), and zoom (whereby only a certain frequency range is analyzed, which can cause aliasing and other problems). The engineer has to make sure that these problems are avoided or minimized and a good coherence level is obtained during the modal survey tests.

One additional problem that is encountered during modal survey testing is the random nature of vibration signals and, consequently, estimation of approximate spectral densities and correlation functions. Generally, it is very important that averaging be performed on several individual time histories, or samples, before a result with a high confidence level is obtained.

All of the abovementioned considerations have been undertaken in the SSME liquid nitrogen tests.

Test Procedure

A high frequency shaker was utilized to excite the structure throughout the duration of the modal tests. Flat-random input loads on the LOX inlet tee generated transfer functions relating the ratio of the response output (from the strain gages on the vanes) over the input force (from the shaker) versus the frequency range of interest (in this case, 3000 to 6000 Hz). These curves were plotted on a log-linear scale and the resonant peaks were indicative of the dominant strain modes. In a similar manner, variation (in time) of the Frequency Response Functions (frf) were plotted consecutively as the liquid nitrogen pressure was slowly increased to 4300 psi and the temperature was ramped down to -240°F. These so called "isoplots" gave a relatively clear indication of the frequency shifts of various strain modes as the test conditions were varied.

The Test Article was appropriately supported on soft material to simulate a "free" condition while the exciter was suspended and acted on the Test Article via a quill and a load cell attached to the end of the stinger. Strain gage and accelerometer data were recorded under three different test conditions and two different excitation point locations. Namely: (1) baseline, (2) with a clamp tied onto the elbow around the splitter vane/shell interface, and (3) with weights (two weights = 21.5 lb each and two weights = 15 lb each) added on the MOV. The excitation points were on the LOX inlet tee and on the elbow near the shell/vane interface.

Two different test regimes were followed: (1) the pressure was ramped up to 4300 psi during the time interval of 80 to 120 seconds, while the temperature was lowered to -240°F in the time interval between 80 and 500 seconds into the test (Fig. 4) and (2) the temperature was asymptotically ramped down from -90 to -255°F between 60 and 900 seconds (Fig. 5), while the pressure was ramped from 0 to 2000 psi during the first 90 seconds and raised linearly during 90 to 860 seconds time intervals up to 4200 psi (Fig. 6).

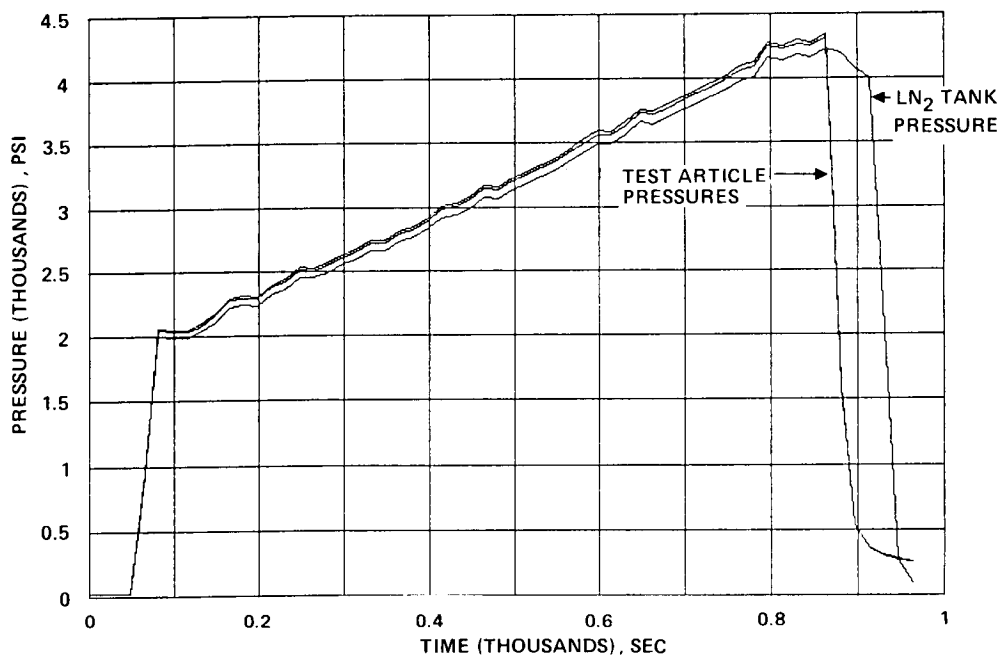


Fig. 4. Pressure vs Time (4000 Hz)

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DATA ANALYSIS AND EVALUATION

In all experimental modal survey tests, data analysis is a fundamental part of the structural dynamic analysis and test evaluation. Data acquisition (collection, recording, transmission, storage, preparation, and qualification), data reduction via appropriate computer software, and functional representation of the test results by means of plots (that are generated by various curve-fitting techniques) all play important roles in the data analysis and evaluation process.

The data gathered during the liquid nitrogen tests are quite extensive. Moreover, the evaluation of such massive data in a scientific manner is a challenge; since approximations and qualitative judgements will have to be

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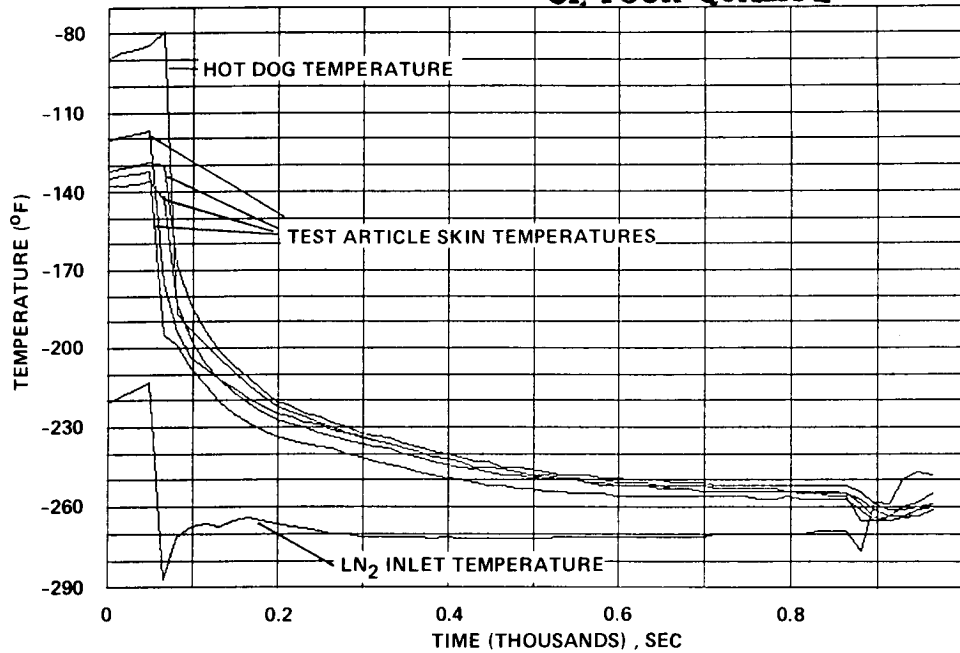


Fig. 5. Temperature vs Time (4000 Hz)

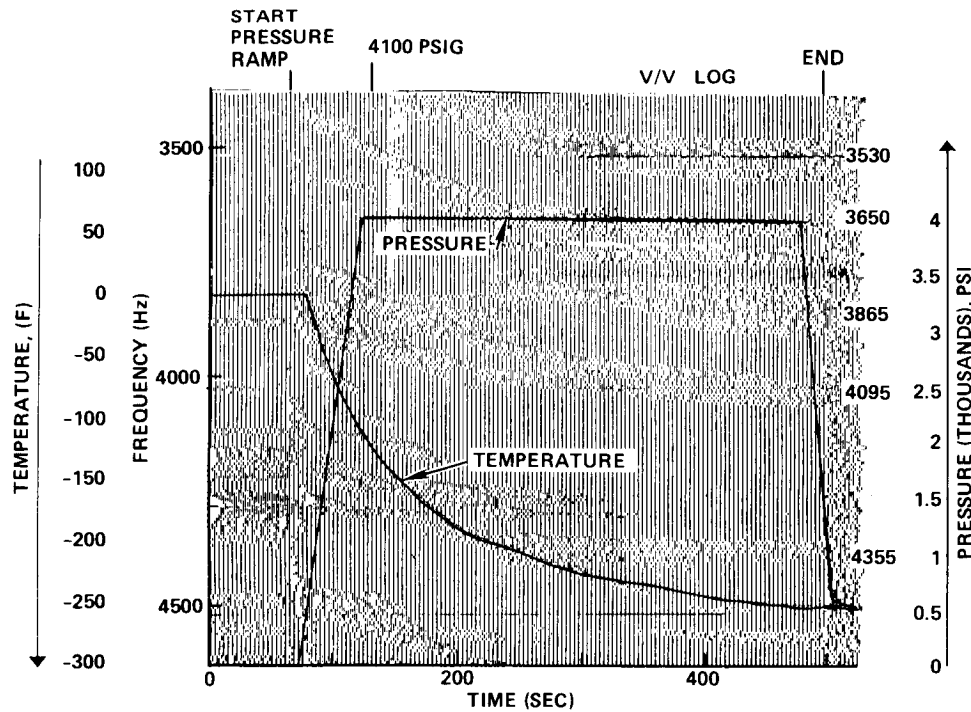


Fig. 6. Liquid Nitrogen Test Article Strain Gage Data
(Right Vane Trailing Edge)

utilized in order to draw meaningful conclusions. Under this light, the modal survey test results, from strain gage measurements of the SSME LOX inlet splitter vanes, provide significant information regarding the shifts of frequencies of various vane modes under different temperatures and pressures.

Baseline

The degree of frequency shifts upwards, due to pressurization and cooling effects, of the splitter vane modes is seemingly a function of frequency. Thus, modes with frequencies in the 3900 to 4100 Hz region experience less shift (less than 300 Hz) as compared to modes at a higher or at a lower frequency (as high as 1000 Hz). Moreover, whether the pressure is slowly increased while ramping the temperature down to -240°F (in about 100 seconds), or the temperature is lowered (exponentially) while the pressure is ramped up, does not change the behavior of the modes, as indicated in the isoplots (Fig. 6 and 7). Reference point frequency response functions from an accelerometer at the shell/vane interface location (Fig. 2) shows the general behavior of modes under baseline conditions as the pressure is increased at low cryogenic temperatures (Fig. 8). Once again, the overall behavior is that modes near 4000 Hz have less of a shift than those at lower or higher frequencies. Furthermore, it is interesting to note that some modes are amplified by increase of pressure while others are completely attenuated, and still others start exhibiting their resonant peaks at higher pressures. All the measurement locations show a response at 4025 Hz frequency starting at around 4000 psi pressure (Fig. 8). These types of behavior might be an indication of nonlinearity (perhaps due to fluid/structure interaction).

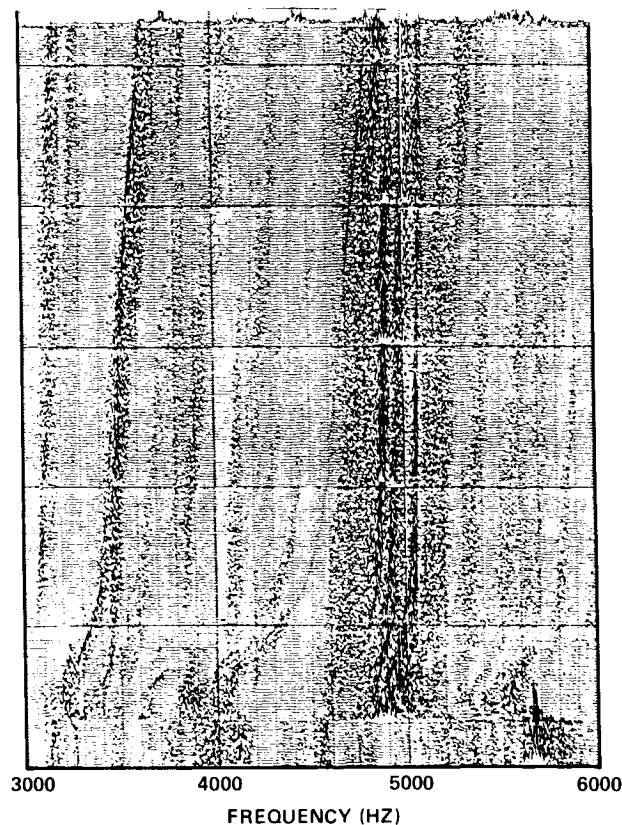
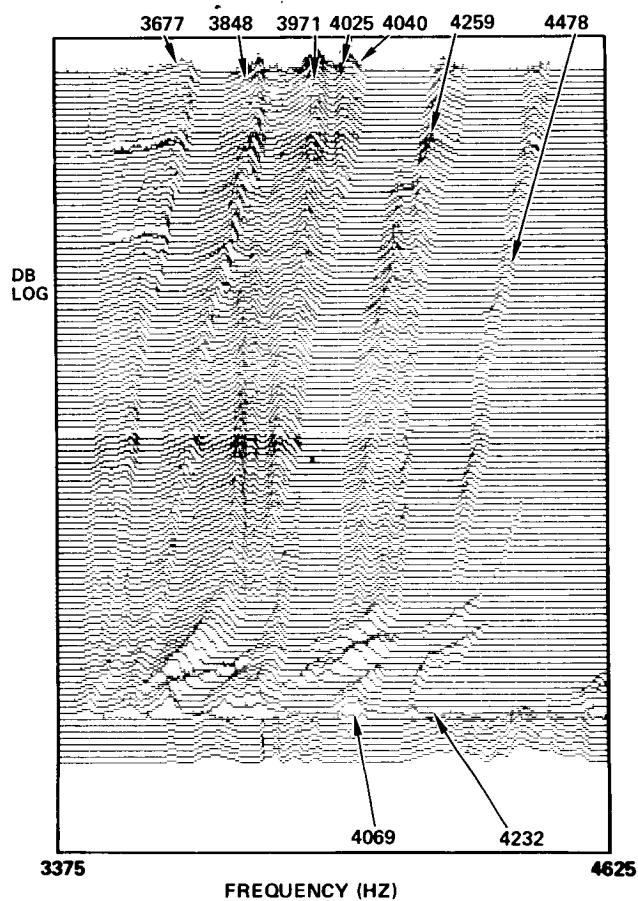


Fig. 7. Liquid Nitrogen Test Article Strain Gage Data
(Right Vane Trailing Edge - 0 Weights)

Quadrature plots (Fig. 9) indicate the phase relationship at each measurement location on the vanes, thus indicating the type of modes that are excited and various frequencies. The 4025-Hz mode seems to be a weak "twisting" mode, whereby the vane free edges move opposite in direction normal to the vane surface. Also, frfs of vanes all exhibit the abovementioned frequency.



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Fig. 8. Liquid Nitrogen Test Article Accelerometer Data
(On the Shell Near Vanes - A1 No Clamp)

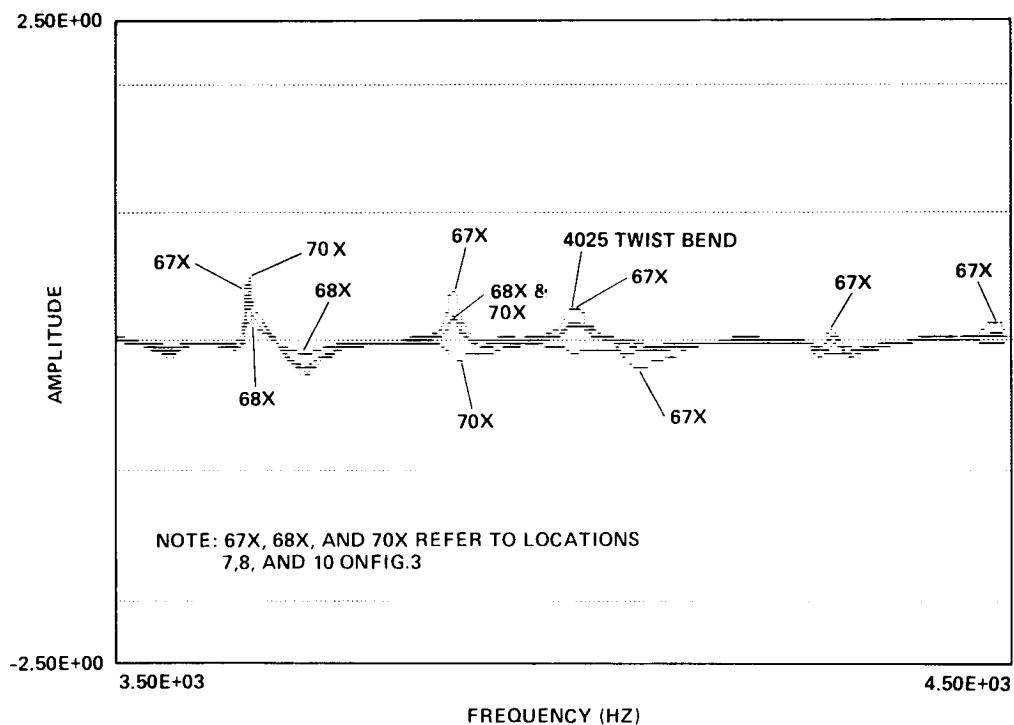


Fig. 9. Imaginary Plots of frf Under Baseline Conditions
(No Weights, No Clamp)

With Weights

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Several weights were added on the main oxidizer valve of the SSME Test Article (Fig. 1) to study the effects and changes that realistic hardware conditions would have on the modal behavior of the LOX inlet splitter vanes. The weights were added in three steps: Two weights of 21.5 lb each at first, then a third weight of 15 lb, and lastly, a fourth weight of 15 lb. The effect of the weight on the modal frequencies and amplitudes are shown in the isoplots (Fig. 10).

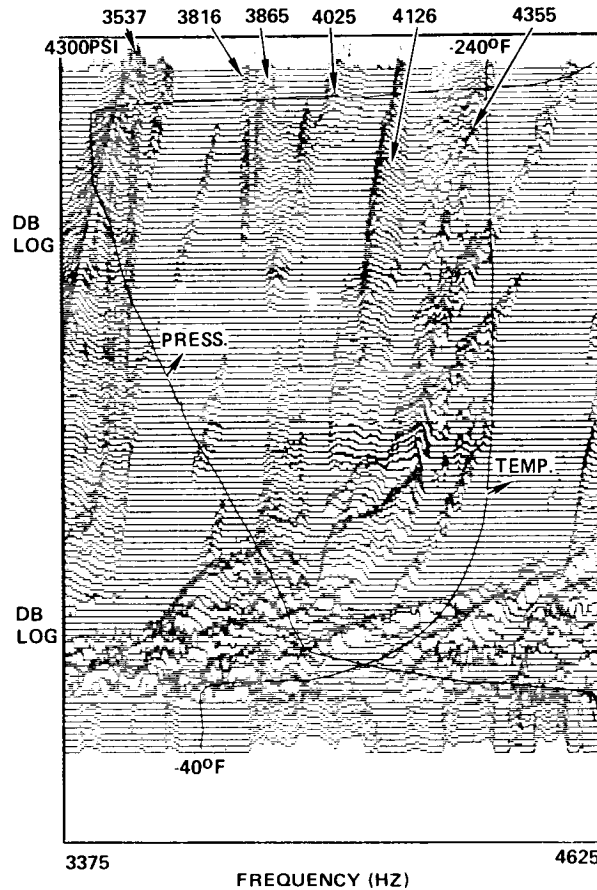


Fig. 10. Liquid Nitrogen Test Article Strain Gage Data
(Right Vane Trailing Edge - 4 Weights, No Clamp)

Once again the frequency shifts are upwards, similar to the previous case. However, many additional modes are excited with the weight on relative to the baseline situations. Moreover, the 4025-Hz frequency is still there with a little higher amplitude again appearing at around 4000 psi pressure. The case of three weights or two weights being somewhat similar to the four weights case; only the latter isoplot is included.

Clamp On

A simple clamp was attached around the splitter vanes on the shell to study the effect of preloading on the vane modal characteristics. Both without weights and with weight cases were considered and isoplots, as well as frfs, were generated for all cases. The general trend of frequency shifts was still prevailing relative to the baseline case, and the frequency shifts upward were

very similar to the previous cases--although with reduced amplitudes (Fig. 11). Specifically, Fig. 11 shows the effect that the clamp has on the isoplots. The 4025-Hz mode is still shown to be there at around 4000 psi pressure. The quadrature plots (Fig. 12) show this mode to be a weak bending mode.

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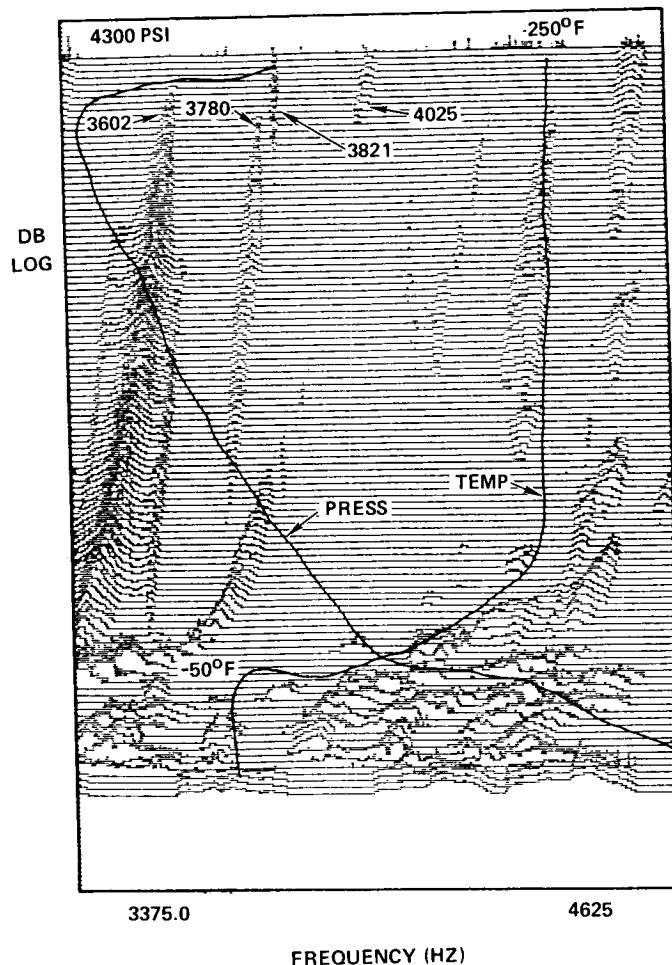


Fig. 11. Liquid Nitrogen Test Article Strain Gage Data
(Right Vane Trailing Edge - 4 Weights, Clamp On)

The overall effect of the clamp is reduction of the amplitudes of vibrations as well as reduction of the response excitation of some dominant modes. The significance of such a fixture is the stiffening effect and damping induced by the clamp on the external shell, which is obviously transmitted to the vanes. The reason for such an experiment was to evaluate the vibration suppression induced by external measures that are simple to implement.

CONCLUSIONS

Pressurization and cooling of metal shells induce frequency shifts upwards (opposite to the influence of wetting the shell from inside). The shifts are a function of frequencies. Preloading, and straining effects also cause variations in the modal behavior, however, the frequency shifts due to the pressure and thermal loading are similar to the baseline case.

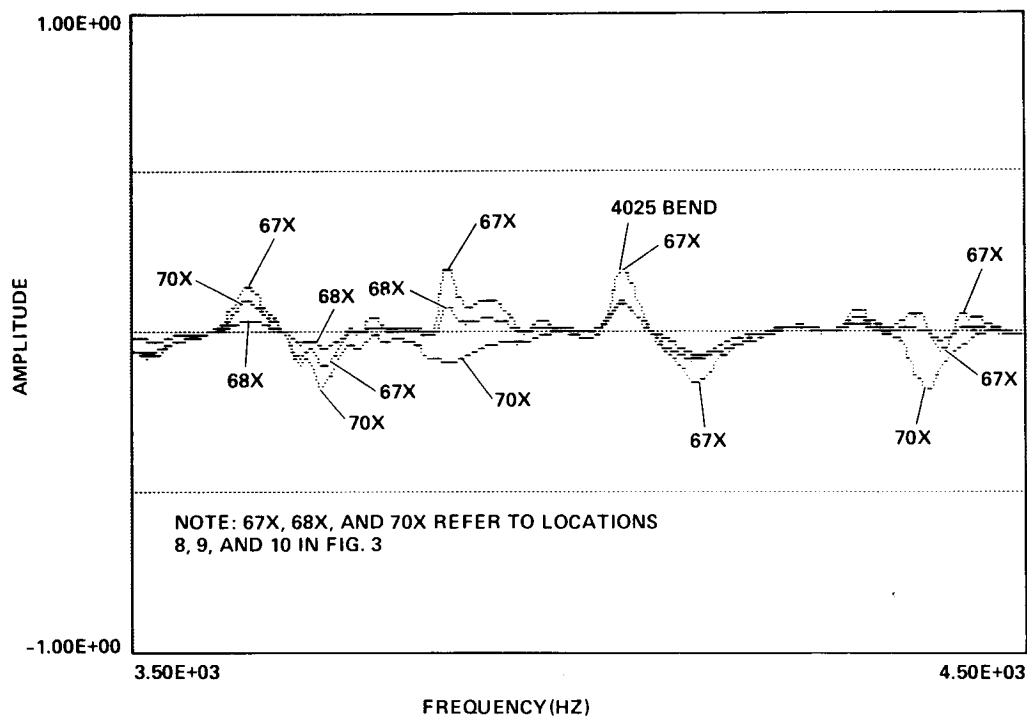


Fig. 12. Liquid Nitrogen Test Article Strain Gage Imaginary Plots
(4 Weights, Clamp On)

Attachment of a clamp around the shell reduces the overall amplitudes of vibration while keeping the frequency shifts virtually constant.

Further studies are needed to correlate the effect of wetting, with those of pressurization and cooling, upon the modal characteristics of metal shells and splitter vanes located in the shells.

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